The Halo from the Outside In: QSO Absorption Lines[1]

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ABSTRACT

Studies of high resolution quasar absorption lines (QALs), arising from gas in local and $z \leq 1.5$ galaxies, provide *direct* probes of the kinematic, chemical, and ionization conditions and evolution of Milky Way–like galaxies. Inferences drawn from these studies provide a powerful analog for those based upon direct studies of the Halo. The observed gas kinematics and velocity evolution reveal that galactic halos are complex dynamical components, consistent with Searle–Zinn formation scenarios.

Introduction

As Sidney van den Bergh stated in his closing comments of the meeting, there are two general approaches to studying the history and evolution of the Galactic Halo. The first is to study the kinematic, chemical, and structural components of the Halo itself, and the second is to study the halos of external galaxies with the partial aim of placing the Halo in the broader context offered by various morphologies and environments (cf. Morrison, this volume). Generally, the tracers of Halo formation (e.g. globular clusters, RR Lyrae stars, Blue Horizontal Branch stars, star counts, etc.) are treated as frozen relics of past formation processes. The hope is that these processes have left signatures, such as kinematic trends or metallicity gradients, which can be used to clearly discern between competing formation scenarios.

One important tracer, which to a certain degree has not captured the attention of those studying Milky Way evolution *per se*, is low density gas in the Halo. Using the absorption lines seen in the spectra of background quasars (QSO Absorption Lines, or QALs), several groups have carefully mapped out the sky locations of large cloud complexes (cf. van Woerden, this volume), including high–velocity clouds (HVCs), which by themselves have a sky covering factor of 38%. The connection between HVCs and Halo tracers is not known, though Majewski (this volume) has reported stellar moving groups which correlate well with the locations and velocities of HVCs toward the North Galactic Pole. From QAL surveys of galaxies at redshifts $0.4 \leq z \leq 2.2$, gaseous halos of normal galaxies are known to extend to ~ 70 kpc and to contain an estimated 10^9–10^{10} $M_\odot$ of gas (Steidel 1993; Steidel & Sargent 1992). Halo gas is the reservoir for star formation and chemical evolution, and plays a central role in the formation of the tracers used to study Halo formation.

[1]to appear in *Formation of the Galactic Halo... Inside and Out*, eds. H. Morrison & A. Sarajedini (PASP Conference Series)

Its study in early epoch galaxies promises to yield important clues to the processes that regulated galaxy formation (cf. Bechtold, this volume).

Learning about the Milky Way from QALs

QAL studies are unique in that they directly probe galactic gas over the entire history of galaxy evolution. Thus, they provide a powerful method from which to indirectly "view" Milky Way Halo formation over a multi–billion year period and offer a very broad context within which studies using Halo tracers can be placed. In tandem with high spatial resolution imaging (Hubble Space Telescope) and high quality spectra of the absorbing galaxies themselves, the potential provided by QAL studies can be fully realized.

From high resolution QAL spectra (see Fig. 1), we can measure the number of clouds intercepted in a galaxy, their column densities, broadening mechanisms, and line–of–sight velocities. HST images provide the absorbing galaxies' environments, luminosities, colors, impact parameters to the QSO (projected galactocentric distance of the absorbing clouds), and orientations relative to the line of sight. Spectra of the galaxies can be used to estimate star formation rates, and (with LRIS on Keck) obtain rotation curves out to $z \sim 1$. Case by case, we can study the physical details of absorbing gas and its relationship to the host galaxy, and then piece together a comprehensive picture of halo evolution directly from the large range of epochs the galaxies sample. The unexplored connections between absorption properties and the locations probed in galaxies, their morphologies, redshifts, and environments will ultimately be used to develop a global picture of kinematic and chemical evolution.

As a first step, we have observed 24 QSOs with the HIRES spectrograph (Vogt et al. 1994). We have resolved absorption profiles of the Mg II $\lambda\lambda 2796, 2803$ resonant doublet in ~ 50 intervening galaxies. Many of these galaxies have been ground–based imaged in the IR/optical and spectroscopically confirmed to have the redshift seen in absorption (Steidel 1995; Steidel, Dickinson, & Persson 1996).

Gaseous Fragments and Kinematic Evolution

In this contribution, we present partial results and a brief discussion of work to be published elsewhere (Churchill & Vogt 1996). In Fig. 1, we show four HIRES/Keck Mg II absorption profiles as seen in the spectra of background QSOs. These absorption lines arise in low ionization gas, which also gives rise to Mg I and Fe II transitions. Generally, these profiles appear to exhibit "characteristics" related to the location and structure probed by the QSO line of sight. In particular, we note the complex high velocity spread in the $z = 0.51$ galaxy toward Q1254 and the $z = 0.92$ galaxy toward Q1206. One could interpret the optically–thick components of these profiles as arising from the disks of these galaxies. The HVC–like optically–thin components are more difficult

to understand. However, they are highly suggestive of a picture in which material in galaxy halos is comprised of kinematically and physically distinct clumps, consistent with the Searle–Zinn (1978) picture of halo formation.

There is a similarity between the features of the $z = 1.17$ profile toward Q1421 and that of the optically–thick components of Q1206. These two QALs may arise in similar structures, or parts of the galaxies. The $z = 1.55$ system toward Q1213 may be a merging or double galaxy, the strength variations in the "double" profile being due to the different line–of–sight orientations, morphologies, and/or masses of the galaxies. HST imaging would be decisive in testing these conjectures. Such inferences can be drawn from QAL studies of local galaxies. Bowen, Blades, & Pettini (1995) have observed a "double" profile similar to that of Q1213 that samples a line of sight passing through both M81 and the Milky Way and spans 400 km s^{-1}. Churchill, Vogt, & Steidel (1995) have observed a possible double galaxy at $z = 0.74$ that exhibits a richly structured "double" profile spanning 300 km s^{-1}. In a ground–based image, there are two galaxies of nearly equal magnitude (redshift?), each with impact parameter ~ 20 kpc.

In Fig. 2, we present the probability, $P(\Delta v)$, of observing any two clouds with line–of–sight velocity difference Δv. The cloud–cloud velocity dispersion within halos exhibits strong redshift evolution, becoming tighter as redshift decreases such that by a look–back time of $\sim$ 8–10h^{-1} Gyr ($h = H_0/100$ km s^{-1} Mpc^{-1}) Mg II absorbing clouds have a mean velocity dispersion ~ 60 km s^{-1}. Such *pronounced* evolution may be due to biasing in our sample selection, since we targeted an absorber population known to exhibit evolution (Steidel & Sargent 1992). Since there is no apparent evolution in the sizes of halos (Steidel & Sargent 1992), or the number of clouds (this study), the implications are that an observable shift may be occurring in the mechanisms giving rise to significant amounts of high velocity material as early as $\sim$ 8 billion years ago. Perhaps we are seeing the epoch at which the frequency of dwarf satellite galaxy accretion onto their primary slows considerably.

We would like to thank the Organizing Committee for hosting an enjoyable meeting and a small travel grant for CWC. Thanks to Jane Charlton, Ken Lanzetta, and Chuck Steidel for insightful on–going discussions. This work has been supported in part by the Sigma Xi Grants–in–Aid of Research program, the California Space Institute, and NASA grant NAGW–3571.

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This preprint was prepared with the AAS LaTeX macros v4.0.

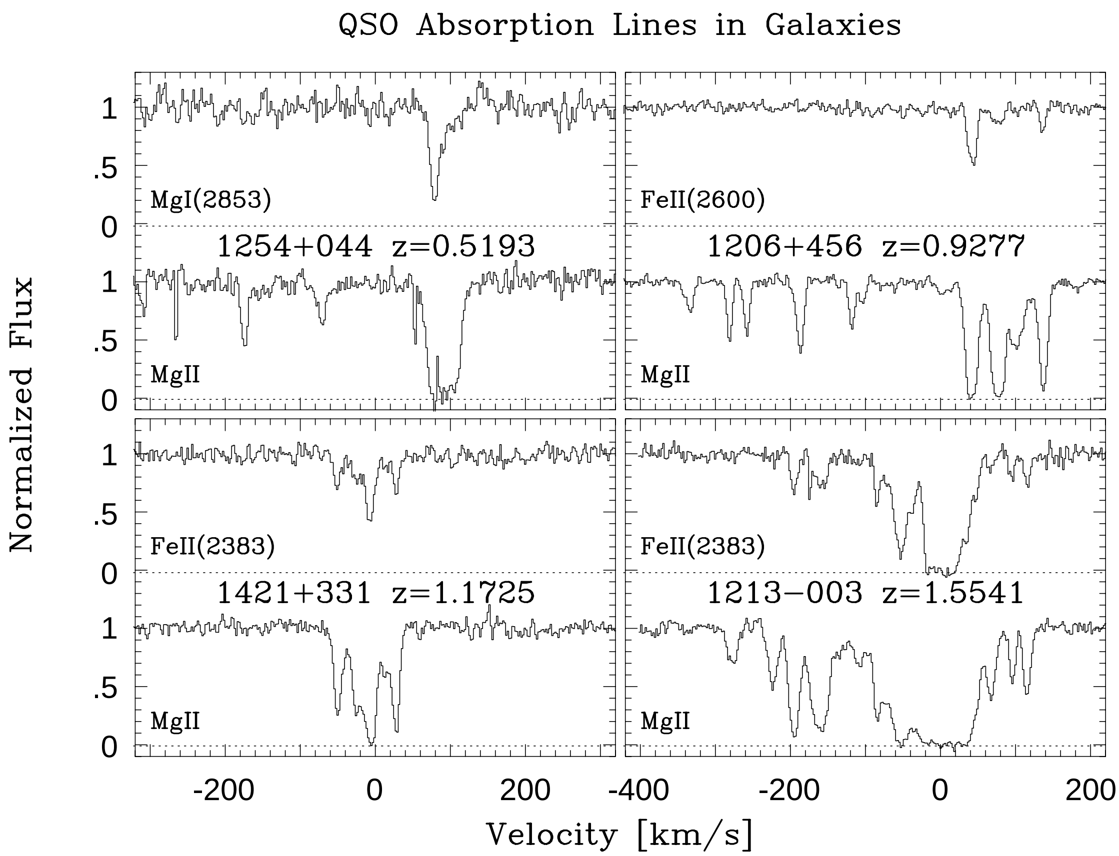

Fig. 1.— Four HIRES/Keck QSO absorption spectra (one per panel) of galaxies intervening to the observed QSO. The QSO and the redshift of the absorbing galaxy are labeled in the panel centers. Two ionic transitions are shown for each galaxy; the lower profile is Mg II (2796) and the upper profile is Mg I (2853) or one of several Fe II transitions.

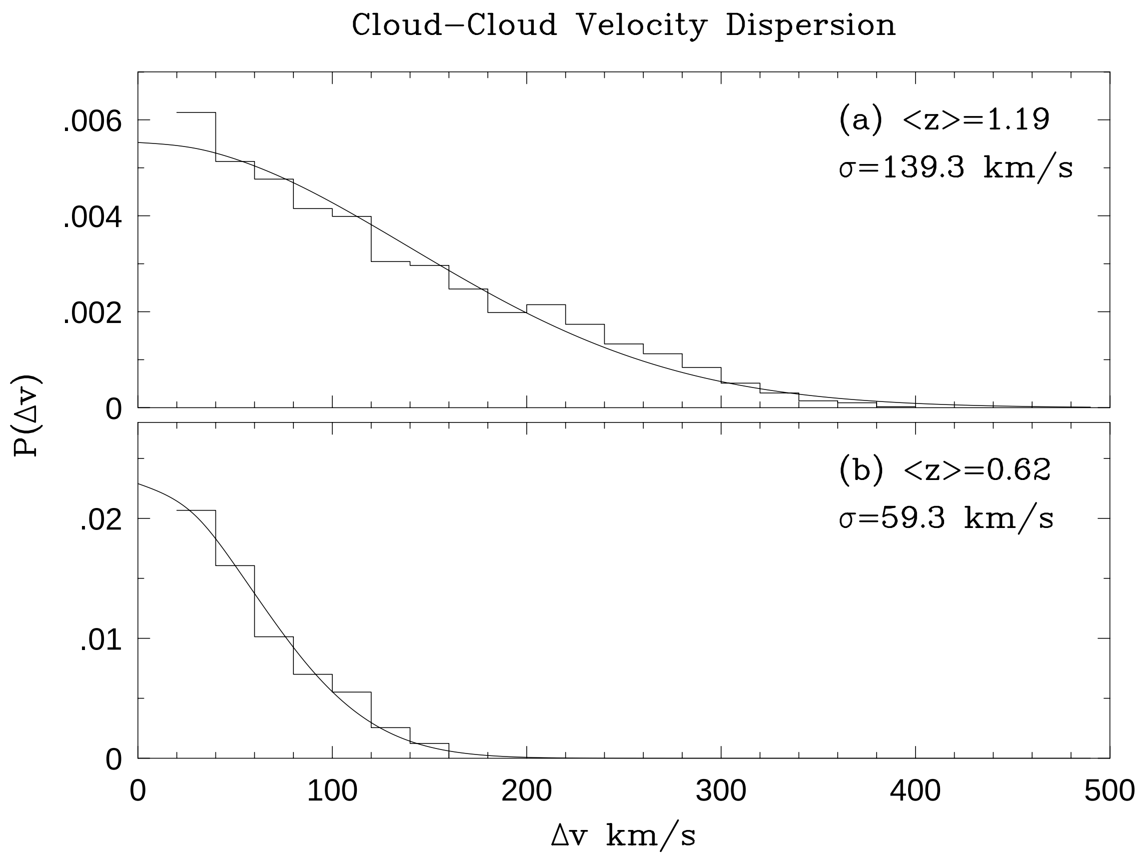

Fig. 2.— The histograms are the observed number of cloud pairs with line–of–sight velocity difference Δv, binned at 20 km s^{-1}. The solid lines are fitted Gaussians, and give the probability of observing any two clouds with Δv. — (a) absorbing galaxies with $z \geq 0.92$ (the sample median), and — (b) those with $z \leq 0.92$.